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# Offshore Wind Power Impact on Peak Load Regulation of Power Systems

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**Abstract**— Peak load regulation in power systems is required to accommodate high levels of power penetration. Wind power generation is a relatively mature technology using renewable energy sources, both on and offshore. Since wind is a random and intermittent resource, the operation of wind power plants depends on peak load regulation of the power grid, which directly affects large-scale wind power integration. In this paper a model is presented to study the capacity of peak load regulation with offshore wind power integration. A CHWG (Coordinated Hydro and Wind Generation) approach is proposed with measures to improve peak load regulation.

**Keywords**- peak load regulation; wind power; offshore wind power; power system analysis.

## I. INTRODUCTION

With a significant increase in installed wind generation capacity power systems are, to a greater extent impacted by stochastic and intermittent wind-flow patterns [1-3]. An analysis shows that wind power output is often lower than 10% of the total wind power installed capacity, [4-7]. In addition, wind forecasting has a limited accuracy. According to the operating experience of the WPMS (wind power management system) [8, 9], even for regional wind prediction errors of forecasting over a 1 – 8h period yield uncertainties in average output power error between 15 – 35%. Limited accuracy in wind forecasting means that it is difficult to predict whether prevalent wind can meet either the peak or trough in expected load. Hence regulation is insufficient and may in fact be grossly incorrect [10, 11].

In China, a wind farm usually includes large numbers of wind turbines which render capacities of hundreds, thousands or even millions of kilowatts. With large-scale penetration of wind, the problem of power system regulation and control is compounded, not least during periods of peak demand. Therefore, it is important to establish a model of the peak load regulation and available capacity and include the influence of available wind resources from on and offshore farms, in order to prescribe measures to govern peak load regulation. Using the Chinese system as a basis for this work, in this paper a

large provincial grid has been assumed, with offshore wind resources subject to an average wind speed of 7.8 m/s and a total installed capacity 1500 MW.

## II. ANALYSIS OF PEAK LOAD REGULATION CAPACITY WITH WIND POWER FLUCTUATION

The actual peak-load regulation capacity of a power grid with significant wind penetration is primarily balanced for load fluctuation; further regulation is used to balance variations in wind input. If the regulation capacity used to balance wind power fluctuations is less than the maximum power output of wind farms, output should be reduced, or completely curtailed [12-14]. In the absence of accurate wind power forecasting, wind generation cannot be accurately assessed in power system scheduling. The generator unit commitment program and operation arrangement are mainly based on the load forecasting, hence generation scheduling from wind farm output is a coarse measure.

### A. Peak Load Regulation Capacity with Wind Power Fluctuation

In practice, all active power output, load and power loss is balanced in a power system [15-17].

$$\sum P_G - \sum P_L - \Delta P_\Sigma = 0 \quad (1)$$

Where,  $\sum P_G$ : total power output;  $\sum P_L$ : total load power; and  $\Delta P_\Sigma$ : total power loss.

When the wind power is integrated to the grid,

$$\sum P'_G + \sum P_W - \sum P_L - \Delta P_\Sigma = 0 \quad (2)$$

Where,  $\sum P_W$  is total wind power output,  $\sum P'_G$ : Other power output after the injection of wind power.

Taking the difference, (2) - (1), we get:

$$\sum P_W = \sum P_G - \sum P'_G \quad (3)$$

$$\text{If } \sum P_W > 0, \text{ so } \sum P'_G < \sum P_G$$

This means that thermal generation can be displaced using for example, wind generation. However, it is also apparent that the variability of wind can be used constructively to influence peak load regulation.

The wind power peak-valley difference is defined by the coefficient  $C$ , where: the wind power output is  $P_{W-\max}$  when load is *peak* (maximum); the wind power output is  $P_{W-\min}$  when load is a *valley* (minimum). The wind farm rated output is  $P_{WR}$ , and the wind power peak-valley difference coefficient can be expressed as:

$$C = \frac{P_{W-\max} - P_{W-\min}}{P_{WR}} \quad (4)$$

$$\text{where, } 0 \leq P_{W-\max} \leq P_{WR}; 0 \leq P_{W-\min} \leq P_{WR}.$$

It can be seen from (4) that  $C \subseteq [-1, 1]$ .

When  $C \subseteq [0, 1]$  the wind power output during a peak load is greater than minimum load and the wind farm output is not affected by the peak power limit.

When  $C \subseteq [-1, 0)$ , the wind output in a peak load is less than that during a minimum load and the wind farm output will be affected by the peak power limit. When  $C = -1$ , the situation is the most serious and the wind farm output at the highest load is 0, and at the lowest load, the output is rated.

The following parameters are proposed:

- $P_O$ : non-coherent load;
- $P_{L-\max}$ : coherent peak load;
- $P_{L-\min}$ : coherent valley load;
- $\beta$ : coherent minimum load rate;
- $P_L$ : difference between coherent peak and valley load;
- $P_A$ : system peak regulation capacity margin without wind power;
- $P_B$ : system peak regulation capacity margin with wind power;
- $P_G$ : unit installed capacity;
- $\lambda$ : unit spare capacity coefficient;
- $\alpha$ : unit power consumption capacity coefficient;
- $\eta$ : the peak load regulation ability coefficient;
- $P_{GH}$ : unit peak load regulation capacity;
- $P_C$ : the external system tie line transmission capacity;
- $\eta_C$ : tie line peak load regulation ability coefficient;
- $P_{CH}$ : external tie line peak load regulation capacity;
- $P_S$ : energy storage capacity;
- $\eta_S$ : energy storage peak load regulation ability coefficient;
- $P_{SH}$ : energy storage peak load regulation capacity;
- $\gamma$ : wind power generation simultaneity factor;
- $P_{WA}$ : wind power output.

A load is composed of *coherent* and *non-coherent* parts. According to a normal operation mode,  $P_{L-\max}$  (coherent peak load) and  $\beta$  (coherent minimum load rate) can be obtained from the load forecasting, and  $P_{L-\min}$  (coherent valley load) can be obtained also:

$$P_{L-\min} = P_{L-\max} \times \beta \quad (5)$$

Peak and valley difference:

$$P_L = P_{L-\max} - P_{L-\min} \quad (6)$$

According to the installed thermal or hydro power capacity  $P_G$  and unit spare capacity coefficient, the unit power consumption capacity coefficient and the peak load regulation ability coefficient  $\eta$ , the peak load regulation capacity of the generator is:

$$P_{GH} = P_G(1-\alpha)(1-\gamma) \times \eta \quad (7)$$

According to the energy storage capacity  $P_S$  and energy storage peak load regulation ability coefficient  $\eta_S$ , the energy storage peak load regulation capacity is:

$$P_{SH} = P_S \times \eta_S \quad (8)$$

According to the external system tie-line transmission capacity  $P_C$  and the tie-line peak load regulation ability coefficient  $\eta_C$ , the external tie line peak load regulation capacity is:

$$P_{CH} = P_C \times \eta_C \quad (9)$$

According to the installed capacity of wind power and wind power generation simultaneity factor, the wind generation is:

$$P_{WA} = P_W \times \gamma \quad (10)$$

Irrespective of the available wind power, the system peak regulation capacity margin  $P_A$  is

$$P_A = \sum_{i=1}^n P_{Gi} \times (1-\alpha_i)(1-\gamma_i) \times \eta_i + \sum_{j=1}^m P_{Sj} \times \eta_{Sj} + \sum_{k=1}^l P_{Ck} \times \eta_{Ck} - P_{L-\max} \times (1-\beta) \quad (11)$$

Where,

- $n$ : number of traditional generators;
- $m$ : number of energy storage power stations;
- $l$ : number of tie lines.

Different generators are distinguished in the equation. By considering the wind output, the system peak regulation capacity margin  $P_B$  is:

$$P_B = P_A - P_W \times \gamma \quad (12)$$

### B. Peak Load Regulation Capacity with Hydro and Wind Coordination

A coordinated hydro and wind generation (CHWG) can be considered for peak load regulation, however hydro output is constrained. Conventional hydropower cannot change randomly and is restrained power system flow. So  $\eta$  (the peak load regulation ability coefficient) cannot provide 100% regulation. However, if wind and hydro sources are

coordinated, wind and hydro output can be used in a complimentary scheme, thus permitting full regulation, such that  $\eta = 100\%$  is attainable [18, 19].

### III. CASE STUDY

A provincial power system model has been used in this case study based on a system in China based on an installed wind capacity of 1,500MW projected for 2015. A conventional hydropower resource provides 6000MW of capacity, which will be used in coordination available wind. The model also includes pumped storage, and gas units which are usually used for frequency regulation. The work presented in this paper is mainly for planning. Therefore the data presented here is statistical. The parameter settings of each generator were established on an individual basis. The power supply of the system consists of three parts:

- 1) Internal power supply, shown in Table I.
- 2) Area contracted power input capacity from nearby provincial power systems, Table II.
- 3) External contracted power input capacity from tie lines to other power systems, shown in Table III.

TABLE I. POWER SUPPLY PARAMETERS OF PROVINCIAL POWER SYSTEM

Unit Type	Installed capacity (MW)	Unit spare capacity coefficient	Unit power plant capacity coefficient	Peak load regulation coefficient
Coal-fired unit	35,240	15%	6%	40%
Oil fuel unit	940	15%	2%	70%
Gas Unit	3,780	15%	2%	100%
Conventional hydropower	6,000	15%	0%	70%
Nuclear power unit	7,310	15%	6%	0%
Wind farm	1,500	0%	0%	0%

TABLE II. AREA CONTRACTED POWER INPUT PARAMETERS

Power supply	Power capacity (MW)	Energy storage peak load regulation coefficient $\eta_s$
Pumped storage power station 1	500	200%
Pumped storage power station 2	540	200%
Pumped storage power station 3	1,310	200%
Tie-line 1	230	100%
Tie-line 2	3,600	50%
Nuclear power	2,090	0%

TABLE III. EXTERNAL CONTRACTED POWER INPUT PARAMETERS

Power supply	External system tie line transmission capacity PC (MW)	Peak load regulation coefficient $\eta_e$
Etie-line 1	1,650	50%
Etie-line 2	1,530	50%
Etie-line 3	4,870	50%
Etie-line 4	2,420	50%

A. The loads are shown in Table IV.

TABLE IV. THE LOADS OF THE PROVINCIAL POWER SYSTEM

Load level	Coherent load (MW)	Non-coherent load (MW)	Overall load (MW)
High project	93,600	3,900	97,500
Middle project	80,180		84,080
Low project	68,100		72,000

#### B. Peak load regulation capacity

The peak load regulation capacity of this provincial power system is calculated as follows, based on coordinated hydro and wind generation.

##### 1) A typical case

If  $P_{L-MAX} = 80180$  MW is assumed, and the coherent minimum load rate:  $\beta = 0.51 \sim 0.70$ , the unit spare capacity coefficient:  $\lambda = 15\%$ , and the wind generation factor:  $\gamma = 0.70$  are established, then Table V and Figure 1 show the results.

From Table V and Figure 1, it can be seen that the changes of a grid minimum load influence the system peak load regulation margin. When a minimum load rate is arranged in the range 0.51 to 0.58, the system cannot provide peak load regulation. When a minimum load rate is arranged in the range 0.51 to 0.62, the system can accept wind power input. When a minimum load rate is arranged in the range 0.60 to 0.70, peak load regulation operates in the range 294 to 8312 MW. If the wind generation factor is 0.70 and a minimum load rate is arranged in the range 0.51 to 0.64, the system peak load regulation capacity margin is negative; the system does not have cannot provide peak load regulation. Thus when a minimum load rate is arranged in the range 0.65 to 0.70, the peak load regulation operates in the range 803 to 4812 MW.

With the introduction of a bundled wind-hydro scheme for peak load regulation, the system peak load regulation margin increases when the minimum load rate decreases.

TABLE V. THE CHANGES OF A POWER GRID MINIMUM LOAD RATE INFLUENCE ON PEAK LOAD REGULATION

$\beta$	$P_A$ (MW)	$P_B$ (MW)	$P_{A1}$ (MW)	$P_{B1}$ (MW)
0.51	-6,922	-10,422	-5,392	-8,892
0.52	-6,120	-9,620	-4,590	-8,090
0.53	-5,318	-8,818	-3,788	-7,288
0.54	-4,516	-8,016	-2,986	-6,486
0.55	-3,715	-7,215	-2,185	-5,685
0.56	-2,913	-6,413	-1,383	-4,883
0.57	-2,111	-5,611	-581	-4,081
0.58	-1,309	-4,809	220	-3,279
0.59	-507	-4,007	1,022	-2,477
0.6	294	-3,206	1,824	-1,676
0.61	1,095	-2,404	2,625	-874
0.62	1,897	-1,602	3,427	-72
0.63	2,699	-800	4,229	729
0.64	3,501	1	5,031	1,531
0.65	4,303	803	5,833	2,333
0.66	5,104	1,604	6,634	3,134
0.67	5,906	2,406	7,436	3,936
0.68	6,708	3,208	8,238	4,738

0.69	7,510	4,010	9,040	5,540
0.7	8,312	4,812	9,842	6,342

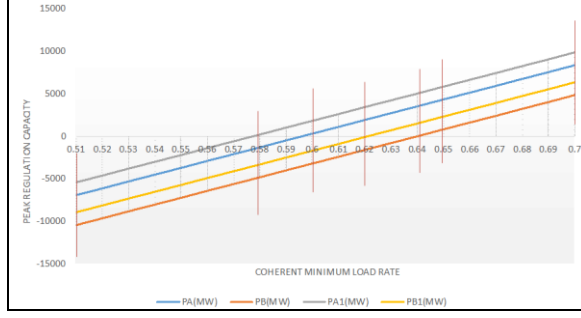


Figure 1. The changes of a power grid minimum load rate influence on the peak load regulation

## 2) Maximum load impact on peak load regulation

In this evaluation  $P_{L-MAX} = 68100 \sim 93600(\text{MW})$ ; the coherent minimum load rate:  $\beta = 0.63$ ; the unit spare capacity coefficient:  $\lambda = 15\%$ ; and the wind power generation factor:  $\gamma = 0.70$ .

It can be concluded from Table VI, that changes in the power grid maximum load will influence system peak load regulation. The system peak load regulation decreased with increasing coherent peak load. Irrespective of the level of wind generation, the system peak load regulation capacity was arranged in the range 509 to 7169 MW when  $P_{L-MAX} \in (68100, 86100)$  MW. When using the CHWG scheme, the system peak load regulation capacity was established in the range 559 to 8699 MW when  $P_{L-MAX} \in (68100, 90100)$  MW. After considering wind power and when wind power generation simultaneity factor is 0.70, the system peak load regulation capacity is arranged 19 to 5,199 MW when  $P_{L-MAX} \in (68100, 82100)$  MW. Obviously CHWG peak load regulation enhanced the acceptance of maximum load capacity.

## 3) Wind power generation factor impact on peak load regulation capacity

In this evaluation:  $P_{L-MAX} = 78,000$  MW,  $\beta = 0.63$ ,  $P_W = 5\text{GW}$ ,  $P_A = 3506\text{MW}$ ,  $P_{AI} = 5036\text{MW}$ ,  $\lambda = 15\%$ , and  $\gamma = 0.50 \sim 1.00$ . It can be concluded from Table VII, that the change in wind power generation factor impacts on peak load regulation capacity. In this study, when the wind power generation factor was higher  $>0.7$ , the system cannot admit large offshore-wind generation. However, when using CWHG operation, the provincial power system can accept all available wind input when the generation factor was 1.

TABLE VI. POWER GRID MAXIMUM LOAD VALUE INFLUENCE ON SYSTEM PEAK REGULATION CAPACITY

$P_{L-MAX}(\text{MW})$	$P_A(\text{MW})$	$P_B(\text{MW})$	$P_{AI}(\text{MW})$	$P_{BI}(\text{MW})$
68,100	7,169	3,669	8,699	5,199
70,100	6,429	2,929	7,959	4,459
72,100	5,689	2,189	7,219	3,719
74,100	4,949	1,449	6,479	2,979
76,100	4,209	709	5,739	2,239
78,100	3,469	-31	4,999	1,499

80,100	2,729	-771	4,259	759
82,100	1,989	-1,511	3,519	19
84,100	1,249	-2,251	2,779	-721
86,100	509	-2,991	2,039	-1,461
88,100	-231	-3,731	1,299	-2,201
90,100	-971	-4,471	559	-2,941
92,100	-1,711	-5,211	-181	-3,681
93,600	-2,266	-5,766	-736	-4,236

TABLE VII. WIND POWER GENERATION FACTOR IMPACT ON PEAK LOAD REGULATION CAPACITY

$\gamma$	$P_B(\text{MW})$	$P_{BI}(\text{MW})$
0.5	1,006	2,536
0.55	756	2,286
0.6	506	2,036
0.65	256	1,786
0.7	6	1,536
0.75	-244	1,286
0.8	-494	1,036
0.85	-744	786
0.9	-994	536
0.95	-1,244	286
1	-1,494	36

## IV. MEASURES TO IMPROVE THE SYSTEM PEAK LOAD REGULATION ABILITY

### A. Improve wind power forecasting accuracy

Wind power peak load regulation capacity is the unpredictable part of wind power. An improvement in wind forecasting accuracy can effectively improve parameters needed for peak load regulation.

### B. Cooperate with the energy storage

Energy storage devices can be used to smooth wind power output effectively. Typical energy storage devices include compressed air, mechanical flywheel, battery, and super capacitors. Energy storage facilities can also be charged during peak wind generation capacity and discharge during absence of wind. Therefore energy storage can effectively control the wind profile.

### C. Improve peak load regulation power structure

From a consideration of economic benefits and safety, nuclear power plants do not have the load regulation ability. Thermal power units are not suitable for adjusting wind power. Since the steam temperature and pressure parameters can change significantly, the service life of a machine can be compromised, and maintenance costs increase. In the condition without putting oil, the normal adjustable output coefficient of conventional large thermal power unit such as 300 MW and 600 MW capacity is 60%; the normal adjustable output coefficient of thermal power unit(100~200MW) is 40%~50%. Furthermore, the efficiency of energy utilization is reduced during adjusting output. Without special water circumstances, hydropower generating units peak load regulation ability is very good and almost 100%. Pumped

storage units can be as load in the valley load periods and as the power supply in the peak load, the peak load regulation ability is close to 200%. Therefore, increasing hydropower and pumped storage units can enhance the peak load regulation ability of power systems.

#### D. CHWG is an effective method to increase the ability of peak load regulation.

CHWG permits regulation during stochastic variations in wind power and this scheme can be used to schedule power balance, therefore predictable and controllable regulation is provided.

### V. CONCLUSION

The CHWG scheme proposed in this paper is an effective approach to improve peak load regulation. In order to maintain system frequency during regulation, power balance should be established at all times in a power system. In traditional power systems, swing generators follow load changes. Large-scale wind power integration challenges the power balance regulation, predominantly because wind is a stochastic resource. In the larger-scale power system being established in China, curtailment and tripping-off of wind generators occurs frequently. For power balance regulation, the regulating capacity of hydro-generators is lower than 70% of normal capacity, but the scheme CHWG makes full use of the hydro-generators normal capacity to balance variations in wind. Using hydro-power, the CHWG scheme directly compensates wind power fluctuation and it is proposed that this scheme could be strategically considered in operation generation scheduling.

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